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Farklı Yağış Yoğunluğu Altında Su Geçirimi Düşük Toprakta Akış ve Sediment Simülasyonu

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Öz

Yağış yoğunluğu ve toprak geçirimsizliğinin, yüzey akış oluşumu ve toprak erozyonunu üzerine etkileri tam olarak anlaşılamamıştır. Bu iki faktör yüzey akışı ve ilişkili olarak sedimenti etkilemektedir. Bu çalışmada, farklı hidrofobiklik seviyeleri altında ve aynı zamanda farklı yapay yağış yoğunluklarına göre yüzey akış ve sediment verimini simüle etmek için "Advanced Hydrological Investigations (AHI)" adlı fiziksel bir model kullanılmıştır. Kumlu tınlı bünyeye sahip bir toprak, beş derece hidrofobiklik elde etmek için farklı yoğunluklarda stearik asit kullanılarak yapay olarak hidrofobikleştirilmiştir. Öte yandan, modelde beş yağış yoğunluğu seviyesi yapay bir yağış olarak kabul edilmiş ve 25 uygulama test edilmiştir. Sonuçlar hidrofibiklik arttığında, yüzey akış hacminde artış, sediment veriminde, derine süzülmede ve suyun havzada toplanma süresinde azalma olduğunu göstermiştir. Ayrıca, toprak geçirimsizlik seviyesinin yükselmesi sediment veriminin düşmesine neden olmuştur. Kontrol konusu ile karşılaştırıldığında(6,5 gr toprak kaybı), aşırı geçirimsiz topraktan 80 litre/saat yağış yoğunluğu altında 2 gr toprak kaybı olmuştur. Hidrofobik toprakta tortu azalmasının olası açıklaması, organik madde içeriği ile pozitif olarak ilişkili olan hidrofobik işlemlerde agrega stabilitesi olabilir.Yüksek derecede geçirimsiz topraklardaki sediment azalması, kurak ve yarı kurak bölgelerde toprak yönetimi politikası olarak düşünülebilir.

Anahtar Kelimeler: Hidrofobi, akış katsayısı, derine sızma, toprak yönetimi, kurak ve yarı kurak bölge

Simulation of Runoff and Sediment in a Water Repellent Soil under Different Rainfall Intensity

Abstract

The impact of rainfall intensity and soil water repellence (SWR) on runoff generation and soil erosion are not fully understood. These two factors affect runoff and the related sediment. In this paper, a physical model, "Advanced Hydrological Investigations" (AHI) was employed to simulate runoff and sediment yield under different degree of hydrophobicity level also in respect with different artificial rainfall intensities. A sandy loam soil was artificially hydrophobized using different concentration of stearic acid to achieve five degrees of repellence (hydrophilic as the control). On the other hand, these five levels of artificial rainfall intensity were considered as an artificial rainfall in the model and finally 25 treatments were tested. The results showed an increase in runoff volume, decrease in sediment yield, and decrease in deep percolation volume and decrease in time of concentration by increasing hydrophobicity. The higher SWR level, the lower sediment yield. It was recorded 2 gr soil loss in extreme repellent soil under 80 l/h rainfall intensity in compare with control treatment of this situation (6.5 gr

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soil loss). Possible explanation of sediment reduction in hydrophobic soil, could be aggregate stability in hydrophobic treatments which is positively related with organic matter content. Sediment reduction in higher degree of SWR could be considered as soil management policy in arid and semi-arid region.

Keywords: Hydrophobicity, Runoff coefficient, Deep percolation, Soil management, Arid and Semi-arid region

INTRODUCTION

The process of run-off and the soil erosion is very complex and is affected by many factors. The specifications of rainfall and soil are two primary factors that affected on the production of run-off and soil erosion (Ran et al., 2012). Generally, rainfall intensity is more effective for the generation of runoff and sediment than total amount of precipitation (Jungerius and ten Harkel, 1994). Rainfall intensity is an important factor (Witter et al. (1991). Higher intensity and/or longer duration leads to an earlier runoff production and consequently higher runoff peak which means larger runoff (Wei et al., 2014; Ran et al., 2012; Peng and Wang, 2012; Dos Santos et al., 2017; Chen et al. 2018). Many researchers have studied the effect of rainfall properties on hydrologic response and soil erosion (De Lima, 1990; De Lima et al., 1992, 2003, 2009; De Lima and Singh, 2003, Da silva et al., 2017). In this research, the effect of soil characteristic on runoff and sediment yield was studied to complete later one.

One of the soil characteristics may affect hydraulic and hydrology of soil is "soil water repellency (SWR)" (Dekker et al., 2005; Gao et al., 2018). The influences of SWR on hydrological response evaluated by Zheng et al. (2017), results showed that by increasing SWR degree, infiltration will be decreased. Zheng et al. (2019) evaluated the erosional behavior of soils with artificially induced water repellency. It was investigated that splash erosion is positively correlated to synthetic water repellency and rainfall intensity. Increasing runoff by increasing SWR is a common result of some studies (Ferreira et al., 2016; Gomi et al., 2008b; Keizer et al., 2005; Miyata et al., 2010; Valeron and Meixner, 2010, Mohammadi et al.,2018). However, a research emphasize on positive effect of soil water repellency in some situations (Blanco-Canqui, 2011). This results is because soil structure play an important role controlling water movement and its ability (Arcenegui et al., 2008). SWR may also prevent soil aggregates from breaking down because of slower water infiltration (Bisdom et al., 1993; Vogelmann et al., 2013). So, both soil aggregate stability (AS) and SWR could regulate soil physical structure and soil chemical distribution. Our aims were 1) to determine directly the impact of SWR on run-off and sedimentation considering different artificial rainfall intensities and 2) to study the effect of AS in water replant soils.

In order to better define the situation of run-off generation and sediment yield, from water-repellent soils under different artificial rainfall intensities a physical model of a special equipment, named "Advanced Hydrological Investigations" (AHI), was developed. To our knowledge, no laboratory-scale measurements to determine directly the impact of SWR on run-off and sedimentation, considering different artificial rainfall intensities, have yet been conducted in arid and semi-arid region

Due to the importance of soil splash erosion and runoff in arid and semiarid regions, and to evaluate the effect of rainfall intensity on runoff and splash erosion in range of hydrophobic soils, this research was conducted for the first time both artificially hydrophobization soil, and directly assessing, Also AS was determined in water repellent soil as an accurate index in the situation.

MATERIALS AND METHOD

Material

Physical model

To simulate runoff and sediment, physical model of a special equipment named "Advanced Hydrological Investigations" which is schematically shown in Figure 1, was employed. Device specification is available in web page of the Gunt[1] Technology firm. The driving force of the equipment includes an electric pump with the power equal to 0.55 KW. There are eight nozzles that provide sprinkler irrigation with square spraying pattern. The spraying flow is adjusted up to max. 1500 l/hr, by a rotameter underneath the equipment. The required water for spraying is stored in a 220 Litre tank. Working with the equipment is easy, and due to the equipment function, its components can be adjusted or changed. Manometers and sumps are removed from the system.

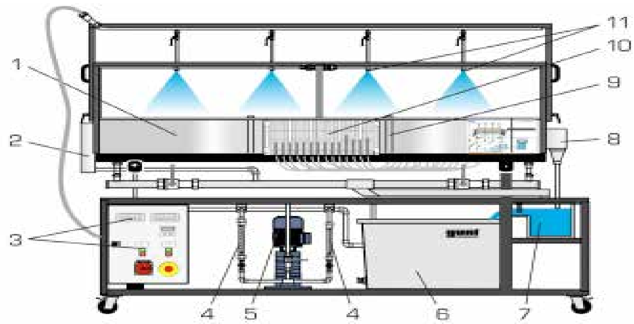

Figure 1. Schematic view of Advanced Hydrological Investigations equipment for the required test)1 experiment tank, 2 chamber, 3 display and control elements, 4 flow meter (supply), 5 pump, 6 storage tank, 7 measuring tank (drain), 8 chamber, 9 well, 10 tube manometers,11 nozzles of the precipitation device).

***Şekil 1.** Gerekli test için Gelişmiş Hidrolojik Araştırma ekipmanının şematik görünümü (1 deney tankı, 2 bölme, 3 ekran ve control birimleri 4 sayaç, 5 pompa, 6 tank, 7 ölçüm tankı, 8 bölme, 9 boşluk, 10 tüp manometreler, 11 başlık ve yağış aygıtları).*

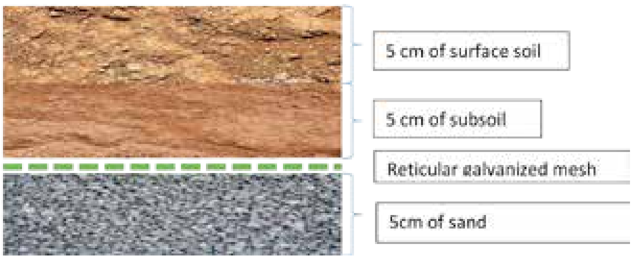

Figure 2. Schematic view from inside the experimental tray
***Şekil 2.** Deney tablasının içten şematik görünüşü*

The equipment consists of a soil tray with 2 m length, 1.2 m width, and 20 cm depth. Due to the 20 cm depth of the tray, the upper 5 cm is considered as the free board space. Five cm of the bottom of the tray was filled by sand in order to facilitate and accelerate the drainage of water (Figure 2). A galvanized mesh is placed on the sand. The upper 5 cm of the 10 cm of soil was considered as the surface soil.

The duration of spraying indicates the working time of the equipment and spraying water by the sprinklers. Spraying was done until the water drops reached to the farthest point of the soil tray.

Runoff was volumetrically measured and sampled continuously for sediment concentration. Collected samples were deposited for 24 h, out of water, dried in a forced-air oven at 105°C until constant mass was achieved, and weighed. Specifications of the used soil.

Soil and Water specification

The soil specifications were determined in the laboratory (Table 1 and 2). The texture of the tested soil is sandy loam. The soil type is Aridisols.

Research methodology

The number of treatments of research includes 5 levels of hydrophobicity and 5 levels of rainfall intensity (total of 25=5*5). In following section the theory of each treatment will be described.

Artificially Hidrophobization of soil

To create the homogeneous hydrophobic conditions in the soil with definite physical specifications, the soil is made hydrophobic artificially by the use of stearic acid ($C_{18}H_{36}O_2$). Stearic acid was chosen because it is a common organic acid in natural soil (Deng and Dixon 2002). Stearic acid is a saturated fatty acid that can deposit on the surface in special conditions (Mojiri and Aliofkhazrae, 2017). The soil hydrophobicity is done in 5 alternative/ different degrees such as hydrophilic (as the control sample), slight repellency, strong repellency, severe repellency, extreme repellency. The amount of the required stearic acid for different hydrophobic levels was determined by WPDT empirical test (Dekker and Ritesma, 1994), together with trial and error considerations.

Table 1. Chemical and physical soil analysis
***Çizelge 1.** Kimyasal ve fiziksel toprak analizi*

Soil property	Sand %	Clay %	Silt %	Lime %	Bulk density (g cm^{-3})	PH	EC ds^{-1}m	Organic Matter %
Amount	58	13	29	32	1.7	7.7	8.4	0.584

EC: Electric Conductivity PH: Power of Hydrogen

Table 2. Chemical analysis of water used for the experiment
***Çizelge 2.** Denemede kullanılan suyun kimyasal ve fiziksel analizi*

So4^{2-} (meq/lit)	HCO_3- (meq/lit)	Mg^+ (meq/lit)	Ca^{2+} (meq/lit)	pH	EC ds^{-1}m
0.15	2.2	0.5	1.5	7.5	0.358

EC: Electric Conductivity PH: Power of Hydrogen

Rainfall Intensity

Rainfall is one of the major active agents of soil erosion, its capability to erode soil, i.e. rainfall erosivity is closely related to the rainfall characteristics such as rainfall intensity, duration, kinetic energy etc. (van Dijk et al., 2002). Considering rainfall erosivity factor (EI30), which is defined based on kinetic energy and is acceptable in various regions of Iran (Sadeghi et. al.2011), the maximum rainfall intensity during 30 minutes of an individual storm in cm h-1- (I30) in Shahrekord rain gauge station, analysed in different return periods using an analytical software, Hyfran. According to rotameter adjustment of physical model, maximum rainfall intensity during 30 minutes in 1000 yr return period was intended based on best fitting probability distribution function, PearsonIII. The hydrophobic soil is wetted with artificial rain under various rain intensity in the possible probability occurring levels of 0%, +10%, -10%, +20%, and -20%. Surely it should be mentioned that rainfall intensity of 0% probability occurring level is equal with base rainfall intensity, and in respect to area of tray (1.2 Square meter), base rainfall intensity is about 100 l/h. So, considered treatments of artificial rainfall intensity was 120, 110, 100, 90 and 80 lph.

Shahrekord plain considered as an example of a semi-arid region. The plain is located 32.316 latitude and 50.83 longitude and is situated at elevation 25 meters above sea level. This station is in a semi-arid region, located in Shahrekord the capital city of Chaharmahal and Bakhtiari Province, Iran. It is topographically situated in the north of the Zagros Mountains. The annual average temperature in Shahrekord is about 11 °C but the minimum and maximum absolute temperatures recorded in Shahrekord during the last 30 years have been -32 °C and 42 °C. Average precipitation in the region is 329.9 mm. By using the physical model in each treatment, the rate of runoff and sediment can be measured.

Also we used a term of Time of concentration, (TOC)”. TOC refer to the time of reaching water drops to the corner of the soil tray in this experiment. The TOC was measured in all the treatments.

Aggregate stability measurement

AS was tested according to WDC (Water Dispersible Clay) method. Rengasamy et al. (1984) develop a general scheme for classifying the dispersive behavior of soil based on a laboratory procedure suitable for routine use. According to this scheme, air dried soil treatments passed through a 2 mm sieve. 4 grams were weighed into a 40 ml transparent jar (10 cm high), care being taken to avoid disturbance of the soil sample. The mixture was left undisturbed for 12 h (overnight). To uniformly mix the suspension, a mechanical stirrer with mid-way stirring at a speed of 90 rev min^{-1} for 30 min. After an appropriate sedimentation time (Loveday, 1974), the dispersed clay was estimated by pipetting 2.5 ml of the suspension from a depth of 2.5 cm. The clay was measured gravimetrically. The percentage of dispersed clay was expressed on an oven-dried soil basis (Equation 1).

$$\mathrm{WDC} = \frac{M_c * V_t / V_{sa}}{m_s} * 100 \qquad (1)$$

Where: m_s, Vsa, Vt, Mc are residual clay mass in oven dish, total volume of suspension (40 ml), volume of soil sample (2.5 ml) and soil mass (4 gr) respectively.

RESULT AND DISCUSSION

Due to little solubility of stearic acid in water, acetone solution was used as the stearic acid solvent (Heryanto et al., 2007). Acetone is available and cheap in Iranian market. The amount of the required stearic acid estimated for different degree of SWR was determined experimentally by water drop penetration time (WPDT (test, together with trial and error considerations (Table 3). In compared with other available measurement methods of determining soil water repellency, the WDPT (water drop penetration

Table 3. The amount of the required stearic acid estimated for different degree of SWR
Çizelge 3. *Farklı toprak geçirimsizlik dereceleri için tahmin edilen gerekli stearik asit miktarı*

Test WPDT (s)	Amount of stearic acid (g Kg^{-1} soil)	The degree of SWR
1	0	class 0, wettable (hydrophilic)
30	12	class 1,slight repellency
300	13	class 2, strong repellency
2000	16	class 3, severe repellency
7200	22	class 4, extreme repellency

time) test is used more than any other techniques in any research because it is not expensive and easy to perform in both the field and laboratory. The only measurement equipment is a simple water dropper and a watch (van't Woudt, 1959; Dekker and Jungerius, 1990; Bisdom et al., 1993; Dekker and Ritsema, 1994). To calculate the WDPT, a droplet of water placed onto the soil surface, and the infiltration time will be recorded (King, 1981). According to general manual (King, 1981), about 20 g soil was used to measure the WDPT. The soil sample was placed into an aluminium Petri dish (70 x 10 mm). A simple water dropper was used and three drops (0.05 mL) of water were dropped carefully onto the prepared soil sample, time of infiltration was recorded. This test will determine the presence of SWR. There is a threshold of 5s to distinguish between wettable and water repellent soils (Bisdom et al., 1993).

The rate of runoff and sedimentation

The results show that by increasing the hydrophobicity degree, the rate of runoff has increased. In all treatments and also in control sample, volume of runoff increase by increasing rainfall intensity (Figure 3a). But as the level of hydrophobicity increases, the rate of sedimentation in runoff decreases, because the rainfall is quickly repelled by the hydrophobic soil and there is no opportunity to wash the soil particles. The highest time of concentration (TOC) in hydrophobic treatments, was observed in class2 of hydrophobicity and the rainfall intensity of -20% base rainfall intensity (Figure 3b). In hydrophobic treatments, due to SWR, runoff generated immediately. It means that, a soil capacity to store water will be limited in a SWR condition (Kobayashi and Shimizu, 2007). This may result in reduction growth (Figure 3b). On the other hand, as the duration rises, the water and soil will more contacted each other and the accumulated sedimentation rate also increases (Figure3c).

The effect of SWR on runoff evaluated by Miyata et al. (2007) as they showed that SWR of surface soils may result in overland flow and so SWR may cause runoff. Results of Müller et al. (2018) showed that repellency accelerate runoff. Also, some evidences reported that generally water repellent conditions cause more runoff and erosion (Witter et al., 1991, Osborn et al., 1964). Our results satisfy these reports about the rate of runoff. But, our findings about volume of sediment shows that the rate of sedimentation will be reduced by increasing SWR (Figure4d). Recent research highlighted the positive impact of subcritical soil water repellency on aggregate stability in no-tillage arable farming (Blanco-Canqui, 2011). In addition, SWR reduces the loss of soil water by evaporation (Hallett, 2007, Gupta et al, 2017, Rye and

Smettem, 2017), which might be significant in arid and semi-arid climates. In addition to mentioned studies above, another positive advantageous of SWR should be sediment management under different rainfall intensity in water repellent soil. Water disposal has caused insignificant mixing of water and soil so the rate of sedimentation is also less by increasing the hydrophobicity level in the surface soil, and in fact the soil hydrophobicity does not allow to wash off the soil particles. But sedimentation will be decreased because there is no chance for water drops to remove soil particles. This result may be because of aggregate stability in condition of hydrophobic soil which is in correlate with organic matter content. AS influences several aspects of a soil's physical behavior, in particular water infiltration and soil erosion (Legout et al. 2005). Arcenegui et al. (2008) suggested that the increase in aggregate stability could be related with water repellency.

Soil aggregate stability

Due to the organic matter content of soils correlate with the hydrophobicity index, hydrophobic soils indirectly would present high strength water-stable aggregates and thus greater resistance to disaggregation. A possible explanation of the observed sedimentation in hydrophobic treatments, is analyzing AS. The results of AS test for each treatment, are presented in figures (4) and (5).

The figures show that WDC decreases by increasing degree of hydrophobicity. Kořenková and Matúš (2015) illustrated that gradual increase in AS can be explained by the increase in soil organic matter content and its hydrophobic properties. As it is obvious, adding stearic acid as an organic acid to hydrophobized soil, play the role of rising organic matter. Igwe and Udegbuhnam (2008) stated that the use of organic matter could be effective in reducing the dispersion of clay.

Also it was mentioned in other researches that the decrease in AS is associated with a decrease in organic matter content (DeBano et al., 1979; Soto et al., 1991). The presence of hydrophobic

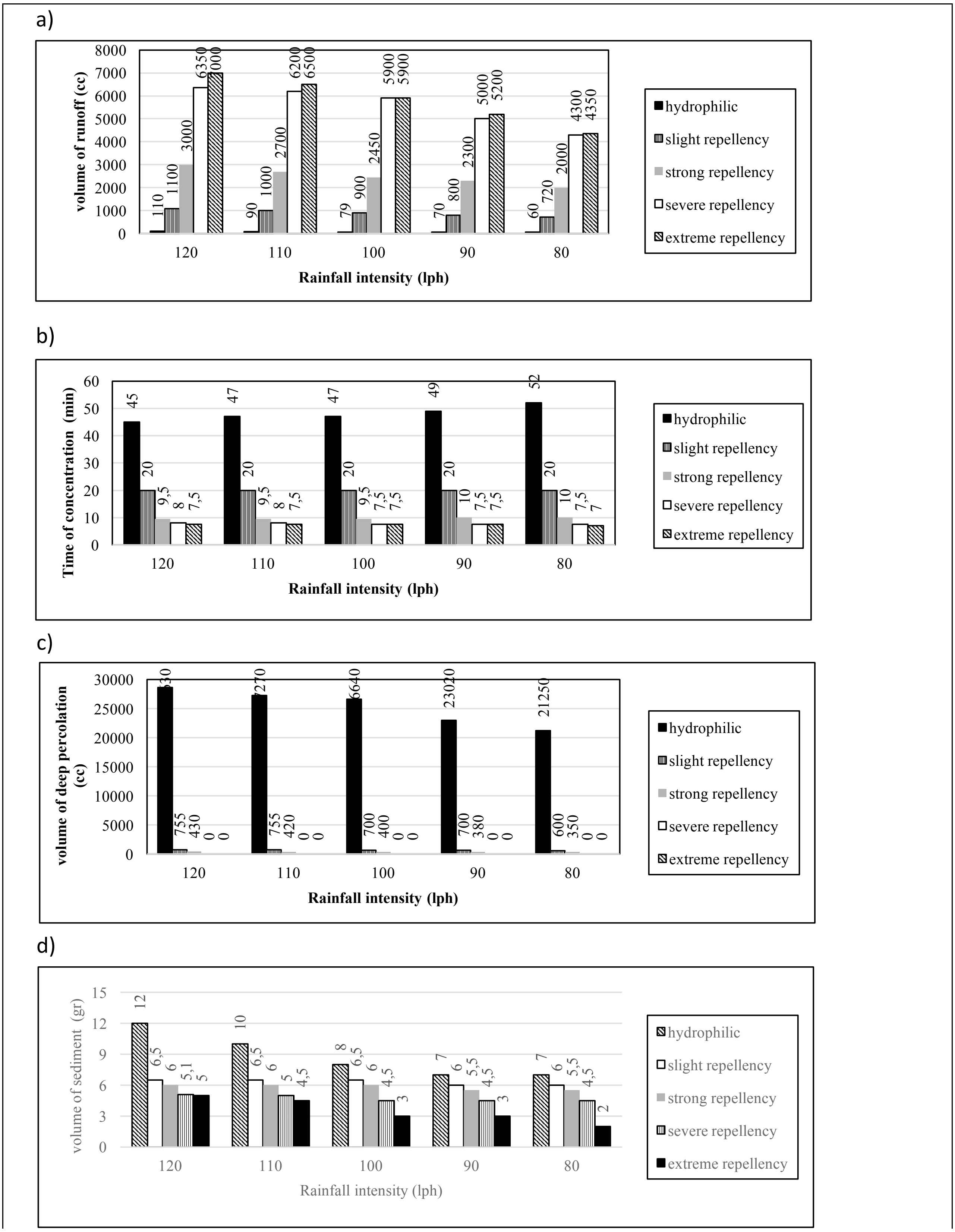

Figure 3. Evaluated value for runoff (a), time of concentration (b) volume of deep percolation (c) and volume of sediment (d)
Şekil 3. *Akış için hesaplanan değer (a), sediment verimi (b), derine sızma hacmi (c), sediment hacmi (d)*

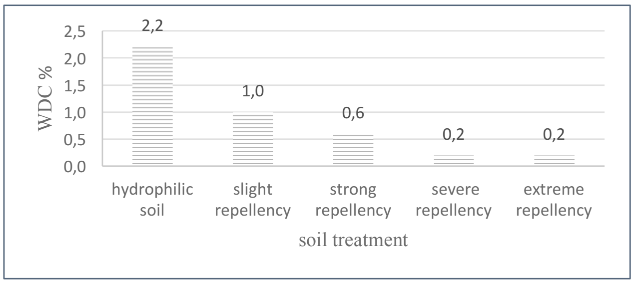

Figure 4. WDC in soil treatment
Şekil 4. *Toprak denemesinde suda dağılabilir kil(WDC)*

compounds can increase the AS. This has been reported by other authors too (Chenu et al., 2000; Hallett et al., 2001; Mataix-Solera and Doerr, 2004; Arcenegui et al., 2008).

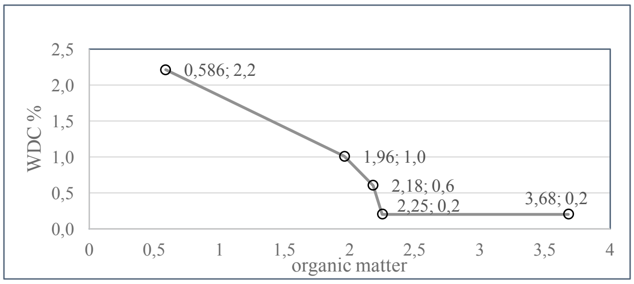

Figure 5. WDC in relation with organic matter
Şekil 5. *Organik madde ile suda dağılabilir kil(WDC) ilişkisi*

Runoff coefficient

Runoff coefficient has been observed in control treatment (hydrophilic) from 0.08 to 0.1 and in 5.5 to 0.92 in hydrophobic treatment. Soil samples with severely and extremely degree of hydrophobicity, (class3 and class4) are completely acted imperviously and similar to the asphalt surface. In these cases, the runoff coefficient is estimated from 0.8 to 0.92 (Figure 4). So, the more hydrophobicity level, the less soil absorption, the less runoff coefficient. This observation is a result of water disposal. The TOC in repulsive soil surfaces is significantly less than the TOC in the absorbable soil surfaces. Our findings satisfy the expected hypothesis that soil characteristic control the speed of rainfall drops to move and reach the corner. The reduced TOC in the hydrophilic soil is due to the water disposal in the soil. There is no water absorb, and thus the water moves rapidly to the corners of the tray. The highest TOC observed in the test was related to the hydrophilic topsoil and the least duration was for to the intense hydrophobic topsoil. Another factor involved in the TOC is the intensity of rainfall. The lower the rainfall intensity, the longer the TOC. Because it requires more time to reach the water drops to the corners of the tray.

If the surface soil is hydrophilic, then the water will not penetrate into the soil immediately after beginning the rainfall, but it will first be deposited on the soil and then it flows to the lower layers if there were microtopography or macrotopography contours. This water movement is a result of finger flow or preferential flow (Ritsma and Decker, 1994). Generally, water repellent soils which have hydrophobic properties can resist or retard surface water infiltration for periods ranging from a few seconds to hours or days (Doerr and Thomas, 2000). The importance of these effects depends upon the severity and spatial variability of SWR (Ritsema and Dekker, 1994). Also Zheng et al. (2017) found that an increase in soil water repellency reduces infiltration and shortens the time for runoff generation, with the effects amplified for high rainfall intensity. This results satisfy our finding. The increase or decrease percent of each measured parameters in compare with the control treatment is reported in Table 5.

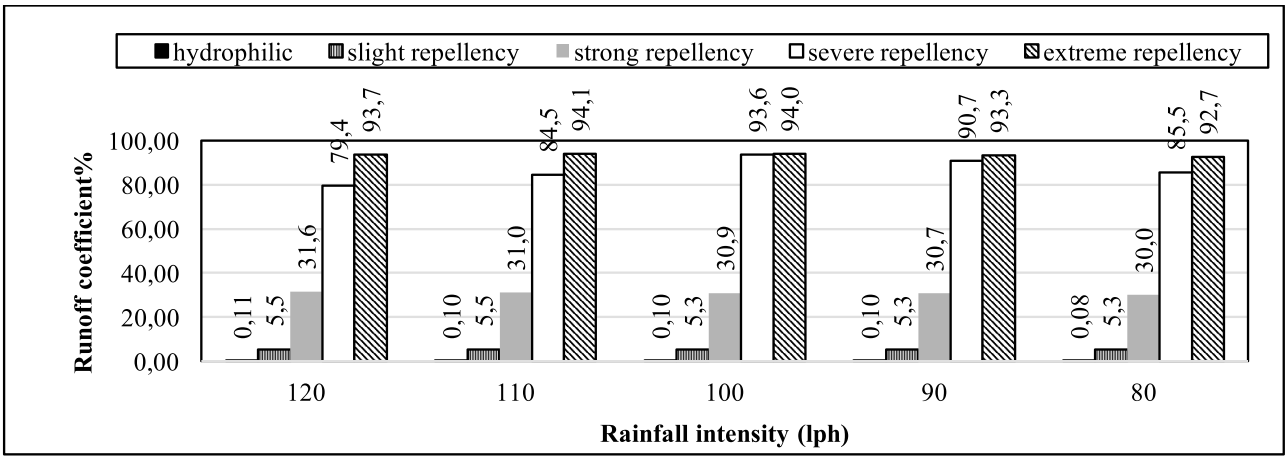

Figure 6. Calculated value of runoff coefficient
Şekil 6. *Hesaplanan akış katsayısı değerleri*

Table 5. Change percent of measured parameters in compare with the control treatment
Çizelge 5. *Kontrol konusu ile karşılaştırıldığında ölçülen parametrelerin yüzdel,k değişimleri*

treatment	Artificial rainfall intensity (lph)	Deep percolation (%)	Time of Concentration (%)	Runoff (%)	Sediment (%)
-slight repellency	120	-97.4	-55.6	1000.0	45.8
	110	-97.2	-57.4	1011.1	-35.0
	100	-97.4	-57.4	1039.2	-18.8
	90	-97.0	-59.2	1042.9	-14.3
	80	-97.2	-61.5	1100.0	-14.3
strong repellency	120	-98.5	-78.9	2900.0	-50.0
	110	-98.5	-79.8	2900.0	-40.0
	100	-98.5	-79.8	3001.3	-25.0
	90	-98.3	-79.6	3185.7	-21.4
	80	-98.4	-80.8	3233.3	-21.4
severe repellency	120	-100.0	-82.2	6250.0	-57.5
	110	-100.0	-83.0	6788.9	-50.0
	100	-100.0	-84.0	7368.4	-43.8
	90	-100.0	-84.7	7042.9	-35.7
	80	-100.0	-85.6	7066.7	-35.7
extreme repellency	120	-100.0	-83.3	6900.0	-58.3
	110	-100.0	-84.0	7122.2	-55.0
	100	-100.0	-84.0	7368.4	-62.5
	90	-100.0	-84.7	7328.6	-57.1
	80	-100.0	-86.5	7150.0	-71.4

The negative sign indicates decrease, in compare with the control treatment. According to this table, by increasing the rainfall intensity level; the rate of deep percolation, TOC have and volume of sediment been decreased in compare with the control sample. By increasing the degree of hydrophobicity; the rate of runoff has increased. The highest observed runoff was 7000cc in severe repellency treatment and the rainfall with +20% Probability, means 120lph. However, the minimum volume of runoff observed in control sample in probability level of -20%, 720 cc. Also, the highest observed sedimentation was 12gr in hydrophilic treatment and the rainfall with +20% Probability, means 120lph. However, the minimum volume of sedimentation is 2 gr which is observed in extreme soil repellency treatment in probability level of -20%. This result indicated the more repellency level the less soil loss as sediment. So SWR would be a suitable management method to decrease soil erosion by decreasing volume of sediment concentration.

CONCLUSION

The following finding has been taken from this research:

In control treatment, the TOC depends only on the rainfall intensity and the maximum TOC is 53 minutes (related to the lowest rainfall level (-20% Probability of the base rainfall) and the minimum TOC is also 47 minutes (related to the highest rainfall level (+ 20% Probability of the base rainfall).

In hydrophobic treatment, due to water repellency, the runoff occurs rapidly, and since the water absorption is negligible, the TOC is shorter than the control sample (hydrophilic soil). In the hydrophilic soil treatments in addition to rainfall intensity, the degree of soil hydrophobicity affects also the rainfall time. The higher the water hydrophobicity, the less TOC.

The less hydrophobicity degree, the less runoff generated. On the other hand, the higher hydrophobicity level, the higher runoff coefficient was observed.

In the hydrophobic soil treatments, the rainfall released into runoff or kept as surface retention. In hydrophobic treatments, except slight and strong repellency, the volume of deep percolation is not observed.

The rate of sedimentation exited along with runoff is decreased by increasing the hydrophobic level. Possible explanation of decreasing sediment yield by increasing soil water hydrophobicity is AS which is because of increasing organic matter content in hydrophobized soil treatment. An advantage of SWR which could be helpful in soil management strategies.

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